Interacting closed string tachyon with generalized Chaplygin gas and its stability

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In this paper, we have considered closed string tachyon model with a constant dilaton field and interacted it with Chaplygin gas for evaluating cosmology parameters. The model has been studied in 26-dimensional that its 22-dimensional is related to compactification on an internal non-flat space and its other 4-dimensions is related to FLRW metric. By taking the internal curvature as a negative constant, we obtained the closed string tachyon potential as a quartic equation. The tachyon field and the scale factor have been achieved as functional of time evolution and geometry of curved space where the behaviour of the scale factor describes an accelerated expansion of the universe. Next, we discussed the stability of our model by introducing a sound speed factor, which one must be, in our case, a positive function. By drawing sound speed against time evolution we investigated stability conditions for non-flat universe in its three stages: early, late and future time. As a result we shall see that in these cases remains an instability at early time and a stability point at late time.

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I. INTRODUCTION

It is known from so many years ago that the String Theory looks like a highly, good candidate to describe the physical world. At low-energies it clearly gives rise to General Relativity, scalar fields and gauge models. In other words, this theory contains in a generic way all the ingredients that overlay our universe. However, at this energy level exist solutions to the effective action related with instabilities, so-called tachyons. Of course, the main reason for discussing this solutions is that they all carry directly over to the superstring theories, where the most well known scenario concerns the presence of a tachyonic mode on the open string spectrum between pairs of D-branes and anti-D-branes [1, 2]. In order to be in the minimal state of energy, the tachyon rolls down to the minimum of the potential, and the perturbative approach of the theory becomes reliable. This process is called tachyon condensation. Notwithstanding, tachyonic modes are not the only solutions on this matter, in fact, in the bosonic string spectrum exist also the closed string tachyon modes. The fact that this scenarios turns out to sit at an unstable point is unfortunate, but the positive thing is that we can think in a good minimum elsewhere for the tachyon potential. To get there we know that an expansion of the tachyon potential around $T = 0$ looks like a polynomial and the physics behind can be reliable.

All these results leads a wide possibility to construct cosmological models that can reproduce the actual behaviour of the observable universe in which an accelerated expansion is present. Interesting solutions emerged as a result of the following studies in the last few years, for example as in [3–7] where the closed string tachyon field drives the collapse of the universe. However, in this attempts an expansion stage is still absent. To defray this line, in [8] the authors considered with the above ideas a compactification of a critical bosonic string theory with a tachyonic potential into a 4-dimensional flat space-time finding certain conditions in where with an arbitrary closed string tachyon potential the universe reaches a maximum size and then undergoes to a stage where collapses as the tachyon arrives to the minimum of its potential.

Regarding to the accelerate stage of the universe, a wide range of research explored the possibility of introduce a viscous fluid coupled to scalar fields. This acceleration as we know can be consequence of the dark energy influence, which in some models the ideal candidate to represent it is the extended Chaplygin gas [9–13], a fluid with negative pressure that begins to dominate the matter content and, at the end, the process of structure formation is driven by cold dark matter

without affecting the previous history of the universe. This kind of Chaplygin gas cosmology has an interesting connection to String Theory via the Nambu-Goto action for a D-brane moving in a $(D+2)$-dimensional space-time, feature than can be regarded to the tachyonic panorama.

Whilst fully realistic models are complicate and have yet to be constructed, this is why the simplicity of the tachyon model coupled with a Chaplygin gas suggested that it may still find some use as a model of accelerated universe. This slope is currently under intense scrutiny and in here we present an attempt to going further.

In our present work we want to choose the closure relation between the above ideas by focusing on the particularity of the model to unify the closed string tachyon and the Chaplygin gas. According to this point of view, the model seems to be an interesting lead since the acceleration stage is preserved. For details of the effects of relaxing these assumptions, we refer the lector to the literature cited below. In Section II we explain briefly the system of equations that represent the closed string tachyon scenario considering a gravitational field in a 4-dimensional non-flat Friedmann–Lemaître-Robertson-Walker (FLRW) metric. We then present the cosmological equations behind this scenario. In Section III we adopt the case when we coupled a Chaplygin gas to the closed string tachyon model [8]. In Section IV we present the description of the full model in the Hamiltonian formalism. We show that, despite the additional freedom in this model, is possible to reconstructed the closed string tachyon potential as we present in Section V and an interesting cosmological analysis was made in Section VI. We conclude in Section VII that this generalized model is capable to describe the current acceleration of the present epoch.

II. CLOSED STRING TACHYON BACKGROUND

Let us start by considering critical bosonic string theory with a constant dilaton. The corresponding action is written for the closed string tachyon field T in 26-dimensional space-time as the following form [3, 7]

$$S = \frac{1}{2\kappa_0^2}\int d^{26}x\sqrt{-g_{26}}\; e^{-2\Phi_0}\left[R - (\nabla T)^2 - 2V(T)\right], \tag{1}$$

where Φ_0, $T(t)$ and $V(T)$ are the constant dilaton, a rolling tachyon field and the closed string tachyon potential, respectively. The 26-dimensional metric, g_{26} is in the form,

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu + h_{mn}dy^m dy^n, \tag{2}$$

where the first r.h.s term denotes a spatially $3+1$ dimensional FLRW metric and indices m, n running from 4 to 25. Thus non-flat FLRW background is given by,

$$ds^2 = -dt^2 + a(t)^2\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right), \tag{3}$$

where k denotes the curvature of space i.e., $k = -1, 0, 1$ are open, flat and closed universe, respectively. Therefore we can write the effective four-dimensional action by compactification on a non-flat internal $22\,d$ space X_{22} as

$$S = \frac{1}{2\kappa_0^2}\int d^4x\sqrt{-g}\; Vol(X_{22})e^{-2\Phi_0}\left[R_4 + \mathcal{R} - (\nabla T)^2 - 2V(T)\right], \tag{4}$$

where $Vol(X_{22})$ is the volume of X_{22}, $\kappa_0^2 = 8\pi G_{26}$ is the gravitational strength in 26 dimensions and $\mathcal{R}$ is constant curvature.

In this model we will consider a constant volume for the internal compact space. Thus the effective $4\,d$ action is written as,

$$S = \frac{m_p^2}{2}\int d^4x\,\sqrt{-g^E}\left[R_4\left(g^E\right) - (\nabla T)^2 - 2\widetilde{V}(T)\right], \tag{5}$$

where m_p^2 and $\widetilde{V}$ are the reduced $4\,d$ mass of Planck and the effective scalar potential respectively, and they are given as the following form,

$$m_p^2 = e^{-2\Phi_0}\frac{Vol(X_{22})}{\kappa_0^2}, \tag{6}$$

$$\widetilde{V}(T) = V(T) - \frac{1}{2}\mathcal{R}. \tag{7}$$

Now by taking $a(t) = e^{\alpha(t)}$ and $m_p = 1$ we can obtain Friedmann equations for action (5) as the following form,

$$\rho_{tot} = 3\left(H^2 + \frac{k}{a^2}\right) = 3\left(\dot{\alpha}^2 + \frac{k}{e^{2\alpha}}\right), \tag{8}$$

$$p_{tot} = -\left(2\dot{H} + 3H^2 + \frac{k}{a^2}\right) = -\left(2\ddot{\alpha} + 3\dot{\alpha}^2 + \frac{k}{e^{2\alpha}}\right), \tag{9}$$

and the equation of the closed string tachyon field is,

$$\ddot{T} + 3\dot{\alpha}\dot{T} + \frac{d\widetilde{V}}{dT} = 0. \tag{10}$$

III. INTERACTING CLOSED STRING TACHYON WITH CHAPLYGIN GAS

In this section, we consider an interaction between the closed string tachyon and Chaplygin gas. The equation of state the generalized Chaplygin gas is given by,

$$p_{ch} = A\rho_{ch} - \frac{B}{\rho_{ch}^{\gamma}}, \tag{11}$$

where p_{ch} and ρ_{ch} are the pressure and energy density of generalized Chaplygin gas where A and B are positive constants and $0 \leq \gamma \leq 1$. Therefore, the total energy density and pressure are given respectively by,

$$\rho_{tot} = \rho_T + \rho_{ch}, \tag{12}$$

$$p_{tot} = p_T + p_{ch}. \tag{13}$$

Now, by taking an energy flow between closed string tachyon and Chaplygin gas, we have to introduce a phenomenological coupling function in terms of product of the Hubble parameter and the energy density of the Chaplygin gas. In that case, continuity equations of the closed string tachyon and Chaplygin gas are written respectively by,

$$\dot{\rho}_T + 3H(\rho_T + p_T) = -Q, \tag{14}$$

$$\dot{\rho}_{ch} + 3H(\rho_{ch} + p_{ch}) = Q, \tag{15}$$

where the quantity Q is the interaction term between tachyon field and the Chaplygin gas and one is equivalent to $Q = 3b^2 H\rho_{ch}$, where b^2 is the coupling parameter or transfer strength [14]. We note that the interaction term Q has widely described in the literature [15–18]. This choice is based on positive motivation Q, because from the observational data at the four years WMAP implies that the coupling parameter must be a small positive value [19].
By substituting (11) into (15) we can obtain energy density of generalized Chaplygin gas as the following form,

$$\rho_{ch} = \left[\frac{B}{\eta} + a^{-3\eta(\gamma+1)}\right]^{\frac{1}{\gamma+1}}, \tag{16}$$

we also obtain the pressure of generalized Chaplygin gas by,

$$p_{ch} = A\left[\frac{B}{\eta} + a^{-3\eta(\gamma+1)}\right]^{\frac{1}{\gamma+1}} - \frac{B}{\left[\frac{B}{\eta} + a^{-3\eta(\gamma+1)}\right]^{\frac{\gamma}{\gamma+1}}}, \tag{17}$$

where $\eta = 1 + b^2 + A$. The energy–momentum tensor is given by,

$$T_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta S}{\delta g^{\mu\nu}}, \tag{18}$$

expression which can be use to rewrite the tachyon energy density and pressure as follow:

$$\rho_T = \frac{1}{2}\dot{T}^2 + \widetilde{V}(T), \tag{19}$$

$$p_T = \frac{1}{2}\dot{T}^2 - \widetilde{V}(T). \tag{20}$$

Finally, considering the previous background, the expressions for the energy density and pressure of closed string tachyon field coupled to Chaplygin gas are

$$\rho_T = 3\left(\dot{\alpha}^2 + \frac{k}{e^{2\alpha}}\right) - \left[\frac{B}{\eta} + a^{-3\eta(\gamma+1)}\right]^{\frac{1}{\gamma+1}}, \tag{21}$$

$$p_T = -\left(\ddot{\alpha} + \frac{3\dot{\alpha}^2}{2} + \frac{k}{2e^{2\alpha}}\right) - A\left[\frac{B}{\eta} + a^{-3\eta(\gamma+1)}\right]^{\frac{1}{\gamma+1}} + \frac{B}{\left[\frac{B}{\eta} + a^{-3\eta(\gamma+1)}\right]^{\frac{\gamma}{\gamma+1}}}. \tag{22}$$

IV. CANONICAL HAMILTONIAN ANALYSIS

In this section we are going to consider the canonical Hamiltonian analysis. For this case, we have to rewrite the lagrangian density of action (5) with respect to generalized parameters $\dot{\alpha}$ and $\dot{T}$. Then, the lagrangian density becomes,

$$S = m_p^2 \int \mathcal{L} dt \tag{23}$$

where

$$\mathcal{L} = \left(-3\dot{\alpha}^2 + \frac{1}{2}\dot{T}^2 - \widetilde{V} - 3\frac{k}{e^{2\alpha}}\right)e^{3\alpha}. \tag{24}$$

By using Hamilton's principle function, we can write canonical Hamiltonian equations and Hamiltonian–Jacobi equation in the following form respectively,

$$\pi_\alpha = \frac{\partial S}{\partial \alpha}, \quad \pi_T = \frac{\partial S}{\partial T}, \quad \dot{\alpha} = \frac{\partial H}{\partial \pi_\alpha}, \quad \dot{T} = \frac{\partial H}{\partial \pi_T}, \tag{25}$$

$$H(\alpha, T, \frac{\partial S}{\partial \alpha}, \frac{\partial S}{\partial T}; t) + \frac{\partial S}{\partial t} = 0, \tag{26}$$

the generalized momenta are written by,

$$\pi_\alpha = \frac{\partial \mathcal{L}}{\partial \dot{\alpha}} = -6\dot{\alpha}e^{3\alpha}, \quad \pi_T = \frac{\partial \mathcal{L}}{\partial \dot{T}} = \dot{T}e^{3\alpha}. \tag{27}$$

On the other hand, the canonical Hamiltonian becomes,

$$H = \sum \dot{q}p - \mathcal{L} = \left(-\frac{\pi_\alpha^2}{12} + \frac{\pi_T^2}{2} + e^{6\alpha}\widetilde{V} + 3ke^{3\alpha}\right)e^{-3\alpha}. \tag{28}$$

Now using Eqs. (26), (27) and (28) we obtain the following Hamilton equation

$$-\frac{1}{12}\left(\frac{\partial S}{\partial \alpha}\right)^2 + \frac{1}{2}\left(\frac{\partial S}{\partial T}\right)^2 + e^{6\alpha}\widetilde{V}(T) + 3ke^{3\alpha} = 0. \tag{29}$$

As we know, the choice of closed string tachyon potential plays the role of an important in String Theory. But we are going to perform the current model for an cosmological analysis. Therefore, different suggestions expressed for selecting of the corresponding potential [20, 21]. In that case, we will extend the job [8] by taking the function S in a non-flat universe by curvature k in the following form,

$$S(\alpha, T) = e^{3\alpha}\left[W(T) + \beta k Z(T)\right], \tag{30}$$

where $W(T)$ and $Z(T)$ are an arbitrary function with dependence on T, and β is a constant coefficient. Now by substituting (30) into (29) the effective tachyon potential is written in terms of functions $W(T)$ and $Z(T)$ as,

$$\widetilde{V}(T) = \frac{3}{4}\left(W + \beta k Z\right)^2 - \frac{1}{2}\left(\partial_T W + \beta k\, \partial_T Z\right)^2 - 3ke^{-3\alpha}. \tag{31}$$

V. RECONSTRUCTING CLOSED STRING TACHYON POTENTIAL

In this section we are going to describe the cosmological evolution of our model with the closed string tachyon coupled to a generalized Chaplygin gas. Let us remark that the recent superstring corrections interpreted compactification on internal manifold that internal curvature is everywhere negative [22, 23]. Therefore, from the point of view $4d$ geometry, the internal curvature is a negative constant $\mathcal{R} < 0$, i.e., the internal curvature is not a functional of T.

In order to obtain effective tachyon potential, we take the function $W(T)$ in the form [8],

$$W(T) = C + DT^2, \tag{32}$$

where C and D are constant coefficients in which they play a role of important for description cosmological solution.

In this model, we simplicity take $W = Z$, then by inserting (32) into (31), the effective tachyon potential is yielded as,

$$\begin{aligned}\widetilde{V}(T) \;=\; & \frac{3}{4}D^2\left(1+2\beta k\right)T^4 + \Big(\frac{3}{2}CD + \frac{3}{4}\beta^2 k^2 D + 3CD\beta k - 2D^2 - 2D^2\beta^2 k^2 - 4D^2\beta k\Big)T^2 \\ & + \left(\frac{3}{4}C^2 + \frac{3}{4}C\beta k^2 + \frac{3}{2}C\beta^2 k - 3e^{-3\alpha}k\right).\end{aligned} \tag{33}$$

As we know, the constant curvature of internal manifold $\mathcal{R}$ is not a functional of tachyon field. Now with correspondence of Eqs. (33) and (7), the negative curvature is given by,

$$\mathcal{R} = -\frac{3}{2}C^2 - \frac{3}{2}k\left(C\beta k + 2C\beta^2 - 4e^{-3\alpha}\right), \tag{34}$$

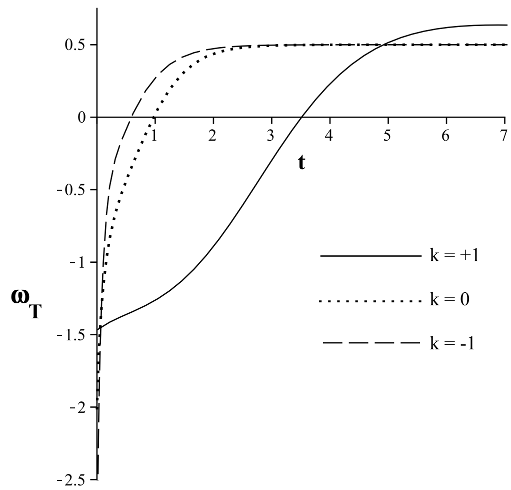

FIG. 1: The EoS of closed string tachyon in terms of time evolution for $B = 8, C = 1, D = -2, b = 0.1, \beta = -0.75, \gamma = 0.05$ and $A = 0.5$ in different cases $k = \pm 1, 0$.

therefore, the closed string tachyon potential is reduced to,

$$V(T) = \frac{3}{4}D^2\left(1 + 2\beta k\right)T^4 + \Big(\frac{3}{2}CD + \frac{3}{4}\beta^2 k^2 D + 3CD\beta k - 2D^2 - 2D^2\beta^2 k^2 - 4D^2\beta k\Big)T^2. \quad (35)$$

By using Eqs. (27), (29), (30) and (32), we can obtain the tachyon field as the following form,

$$T = e^{2D(1+\beta k)t}, \quad (36)$$

then, the scale factor will obtain by Eqs. (27) and (30) as,

$$a(t) = exp\left[-\frac{1}{2}C(1+\beta k)t - \frac{1}{8}e^{4D(1+\beta k)t}\right]. \quad (37)$$

By reinserting (37) into Eqs. (21) and (22) the Equation of State (EoS) of the closed string tachyon is obtained as,

$$\omega_T = \frac{p_T}{\rho_T} = \frac{-\left(\ddot{\alpha} + \frac{3\dot{\alpha}^2}{2} + \frac{k}{2e^{2\alpha}}\right) - A\,\rho_{ch} + \frac{B}{\rho_{ch}^{\gamma}}}{3(\dot{\alpha}^2 + \frac{k}{e^{2\alpha}}) - \rho_{ch}}. \quad (38)$$

We can see variation of the EoS against time evolution by interacting Chaplygin gas with the closed string tachyon by geometries ($k = 0, \pm 1$) in the Figure 1. We note that chosen coefficients play the role of an important to plot the EoS. Then, the motivation of the selections is based on crossing EoS over phantom-divide-line.

VI. CONDITIONS FOR AN ACCELERATED UNIVERSE AND THE STABILITY ANALYSIS

In this section, we are going to investigate two issues: first, the condition of an accelerated universe in our model and second, the stability analysis of aforesaid proposal.

On one hand, we study on the condition of expanding universe accelerating for the closed string tachyon. For this purpose, we can obtain ρ_T, and p_T by inserting (37) into Eqs. (21) and (22) as follows,

$$\begin{aligned}\rho_T \;=\; & \frac{3}{4}(1+\beta\,k)^2\,\left[C+D\,e^{4D(1+\beta k)t}\right]^2+3k\,exp\left[C(1+\beta k)t+\frac{1}{4}e^{4D(1+\beta k)t}\right]\\ & -\left(\frac{B}{\eta}+exp\left[\frac{3}{2}C\eta(\gamma+1)(1+\beta k)t+\frac{3}{8}\eta(\gamma+1)e^{4D(1+\beta k)t}\right]\right)^{\frac{1}{\gamma+1}}, \end{aligned} \tag{39}$$

$$\begin{aligned}p_T \;=\; & 2D^2(1+\beta\,k)^2\,e^{4D(1+\beta k)t}-\frac{3}{8}(1+\beta\,k)^2\,\left(C+D\,e^{4D(1+\beta k)t}\right)^2-\frac{k}{2}\,exp\left[C(1+\beta k)t+\frac{1}{4}e^{4D(1+\beta k)t}\right]\\ & -A\left(\frac{B}{\eta}+exp\left[\frac{3}{2}C\eta(\gamma+1)(1+\beta k)t+\frac{3}{8}\eta(\gamma+1)e^{4D(1+\beta k)t}\right]\right)^{\frac{1}{\gamma+1}}. \end{aligned} \tag{40}$$

Now we can find a constraint for the accelerated universe by weak energy condition ($\rho>0$ and $p_T+\rho_T>0$) in terms of current epoch time t_0, in the following form,

$$\begin{aligned}& \frac{3}{4}(1+\beta\,k)^2\,\left(C+D\,e^{4D(1+\beta k)t_0}\right)^2+3k\,exp\left[C(1+\beta k)t_0+\frac{1}{4}e^{4D(1+\beta k)t_0}\right]\\ & -\left(\frac{B}{\eta}+exp\left[\frac{3}{2}C\eta(\gamma+1)(1+\beta k)t_0+\frac{3}{8}\eta(\gamma+1)e^{4D(1+\beta k)t_0}\right]\right)^{\frac{1}{\gamma+1}}>0, \end{aligned} \tag{41}$$

and

$$\begin{aligned}& 2D^2(1+\beta\,k)^2\,e^{4D(1+\beta k)t_0}+\frac{3}{8}(1+\beta\,k)^2\,\left(C+D\,e^{4D(1+\beta k)t_0}\right)^2+\frac{5k}{2}\,exp\left(C(1+\beta k)t_0+\frac{1}{4}e^{4D(1+\beta k)t_0}\right)\\ & -(A+1)\left[\frac{B}{\eta}+exp\left(\frac{3}{2}C\eta(\gamma+1)(1+\beta k)t_0+\frac{3}{8}\eta(\gamma+1)e^{4D(1+\beta k)t_0}\right)\right]^{\frac{1}{\gamma+1}}>0, \end{aligned} \tag{42}$$

Eqs. (41) and (42) are a constraints for all the coefficients of the model in the current epoch of the universe.

On the other hand, we will discuss the stability of our model with presence of closed string tachyon field. In that case, we will describe the corresponding stability with an useful function $c_s^2=\dot{p}_T/\dot{\rho}_T$. The stability condition occurs when the function c_s^2 becomes bigger than zero. Of course this function represent sound speed in a perfect fluid. By making derivative Eqs. (21)

and (22) with respect to time evolution and numerical computing the function c_s^2 in terms of time evolution, we can plot speed sound function by various geometries ($k = 0, \pm 1$) in Figure 2.
The Fig. 2(a) shows a closed universe, hence we have instability in early time and we have stability in late time that in future time tend to instability case. The flat universe is showed in the Fig. 2(b) that there is instability in early time evolution and there is stability in late time. Notice that the Fig. 2(b) has a eternal steady behavior in future time. In the Fig. 2(c), we can see instability in early time evolution, but in late time exists stability, thus in future time we can see stability by increasing time evolution.

VII. CONCLUSIONS

In this paper, we have studied closed string tachyon with a constant dilaton field in $26d$ space-time for describing something mysterious in the cosmology. To understand this issue, we

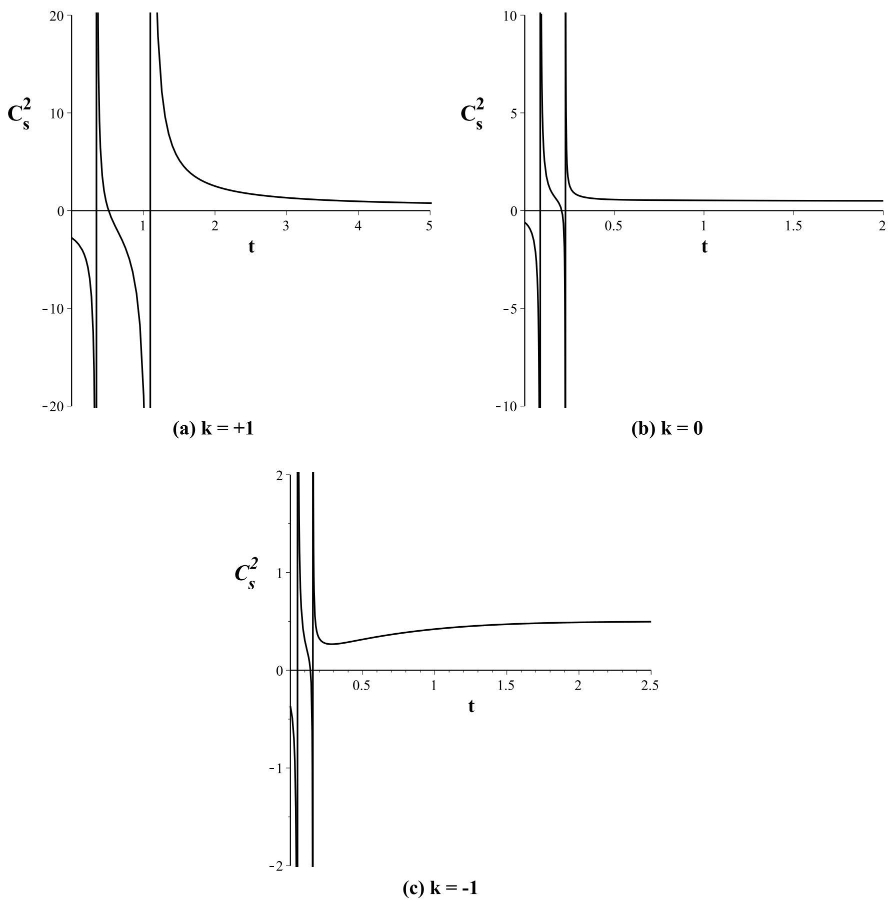

FIG. 2: Graphs of the c_s^2 in terms of time evolution in geometries $k = \pm 1, 0$.

have considered the corresponding model by interacting with generalized Chaplygin gas. We noted that the corresponding action has been written as an effective four-dimensional action by compactification on a non-flat internal 22 d, in which the internal compact space considered a constant volume. The Einstein and field equations have been obtained and by taking an interaction between the closed string tachyon with generalized Chaplygin gas we could find the energy density and pressure of closed string tachyon.

By using canonical Hamiltonian analysis and the corresponding action, we obtained the continuity equation and then the effective tachyon potential have been found in terms of an arbitrary function ($W(T)$ and $Z(T)$) proportional to tachyon field. In order to reconstruct closed string tachyon potential, we took arbitrary function $W(T)$ such as a quadratic function of tachyon field. In additional, by employing canonical Hamiltonian equations we obtained the tachyon field and the scale factor in terms of time evolution. One of cosmology characteristics that confirm observational data is based on the crossing EoS from phantom-divide-line, in which one calculated in terms of time evolution. Also we plotted EoS with respect to time evolution for various geometries. The graph of EoS showed accelerating universe and cross over phantom-divided line. Next we obtained a constraint by weak energy condition. Finally we have considered stability analysis for the presented model by using an useful function called the sound speed. This latter is employed in a perfect fluid, in which its value is greater than zero. It should be noted that the time evolution of sound speed in various geometries showed that there is an stability at late and future times in all of geometries. The interesting problem here was to consider the model with the curvature of the internal space in a non-constant internal volume scenario.

VIII. ACKNOWLEDGEMENTS

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